DRAFT (Jan. 28, 2013)

Predictive Models of Water Quality, Sediment Transport, and Food Webs in Puget Sound and Georgia Basin

Status and Gaps in Model Development

Puget Sound Environmental Monitoring Program (PSEMP)

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Introduction

Modeling is a tool for exploring hypotheses about how the environment works, especially when many systems, including human society, are interacting. Models can help to understand the present state, and to evaluate the outcome of future scenarios, e.g. the effect of scattering ground oyster shells on Ocean Acidification, or the effect of nitrogen releases from sources such as: sewage treatment plants, tributaries, and septic systems on algae growth and oxygen conditions. There are currently several technical groups developing models of circulation, water quality, sediment transport, food webs, and other characteristics of Puget Sound region. In recent years there have been huge advances especially in realistic simulation of 3D circulation fields, thereby enabling new capabilities in spatially explicit ecosystem modeling. Our goal is to fully integrate these new capabilities into the decision-making tools we use to protect the health of the Sound. Below we describe some of the available tools, and we identify key gaps and opportunities. Our highest priorities are for (i) maintenance of shared observational databases used to force and test models, and (ii) long term support for maintenance, improvement, and expansion of key modeling frameworks that will be of use for a wide variety of problems.

This document describes the status of the development and application of mathematical models of water quality in the Puget Sound and Georgia Basin. The focus of this document is marine models of water movement and water quality of Puget Sound.

Background: Marine Models and Puget Sound Partnership Dashboard Indicators

Hydrodynamic and water quality models are critical to evaluating several Dashboard Indicators. The following figure shows areas where models are currently being developed and applied to evaluate an indicator, and areas where modelers indirectly aid in building the information base for indicator assessment.

Figure 1: Indicators Assessed with Models

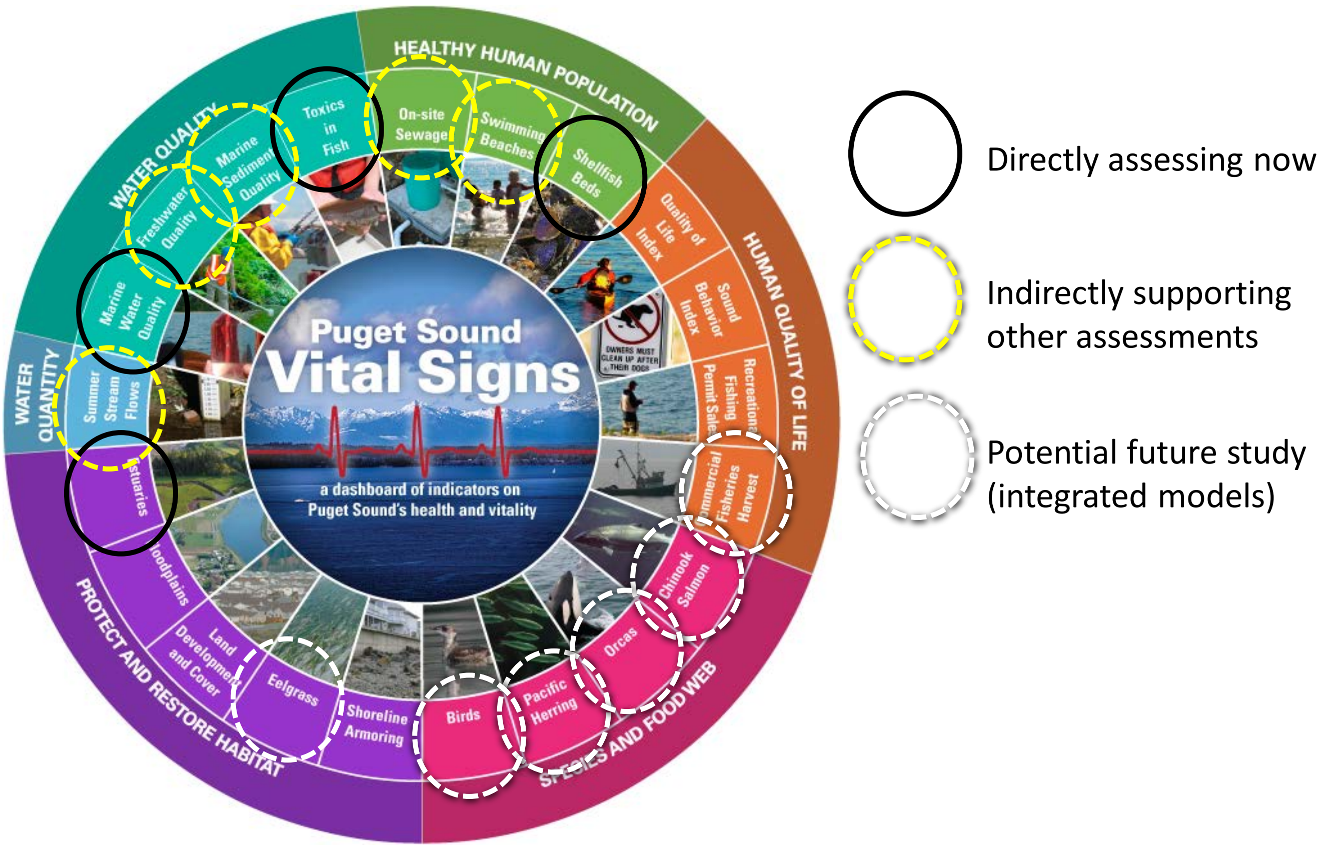

Table 1: Summary of Models and Indicator Assessment

Dashboard Indicator	Target	Role of models	Examples
Marine Water Quality	Maintaining dissolved oxygen impacts below 0.2 mg/L Additional concerns include bacteria, metals(Cu), turbidity, harmful algal blooms, nearshore salinity and/or temperature alteration, and pH.	Models are fundamental to analysis of the primary indicator and broader concerns. Models bring together nutrient/oxygen dynamics, human loadings, natural conditions (including marine nutrient influx) to estimate current/future impacts.	Ongoing studies using models in South Sound, Whidbey Basin, and Budd Inlet Dyes/Sinclair Inlet and Hood Canal studies *Alexandrium* HAB studies (UW/NOAA) Others
Toxics in Fish (Food Web)	Reducing levels of PCBs, PAHs, and EDCs and related compounds in salmon, herring, and English sole below thresholds for human and aquatic life health.	Models provide linkage of source-to-water-to-biota to better understand and prioritize key sources and uncertainties	Puget Sound Toxics Box Model analysis of PCB sources/sinks and bioaccumulation in invertebrates, fish, birds, and marine mammals (food web).
Marine Sediment Quality	Meet sediment quality indices for Puget Sound Regions	Sources and sinks of contaminants in sediments, bioavailability of contaminants and benthic community health. Biogeochemical cycling and digenesis.	Puget Sound Toxics Box Model, sediment transport models, and biogeochemical models Duwamish Superfund site modeling
Estuaries	Restore over 7,000 acres of estuary habitat	Hydrodynamic and sediment transport models help identify effects of dike removal and other near-shore actions on circulation, sediment deposition, and water quality.	Nisqually Delta, Skagit Delta, Snohomish Delta and Stillaguamish circulation and sediment transport predictions in support of dike removal and habitat restoration plans.
Shellfish Beds	Re-open 10,000 acres closed to harvest due to pollution	Models provide estimated transport paths for bacteria, such as plume tracking for point sources and/or tributary inputs to shallow estuaries. Food web model can help understand provisioning and carbon cycling	Oakland Bay stormwater and CSO analysis; Sinclair/Dyes CSO modeling helped reopen 1500 acres of shellfish beds

Status of Ongoing Model Development and Application:

A brief description of the status of larger scale models is included below. The focus on large scale models is based on the need for longer-term, programmatic funding to develop and maintain these models. Smaller embayment models are more suited to focused study, with boundary conditions support by larger scale models and related monitoring.

Puget Sound/Georgia Basin Model

Model development leads:
Tarang Khangaonkar (Battelle-PNNL), Brandon Sackmann (Ecology)

This model has been developed and documented (see reference listing below) by Ecology and PNNL with EPA funding (note: University of Washington is also a collaborator on climate change aspects). The model is the first application of a linkage between the FVCOM model (for hydrodynamics) and CE-QUAL-ICM (water quality) developed by PNNL (Kim and Khangaonkar 2011). Since the early effort to simulate phytoplankton blooms in the main basin of Puget Sound by Winter et al. (1975), it is the first model of its kind to simulate currents, temperature, salinity, nutrients, phytoplankton, and dissolved oxygen for the entire domain of Puget Sound/Georgia Basin (Khangaonkar et al. 2011, Khangaonkar et al. 2012). Ecology/PNNL/UW are currently in the process of applying the model to predict future impacts of human-caused nutrient pollution on dissolved oxygen conditions in the Sound and Georgia Basin. The focus of the current study is large scale changes to oxygen in the main basins. Analysis of shallow basins will require additional, targeted model development and calibration.

EPA and Ecology are very encouraged by the performance of this model to date and anticipate that it will become a “workhorse” model for analysis of Puget Sound water quality and circulation in support of Puget Sound Partnership goals.

MoSSea (Modeling the Salish Sea)

Model development leads:
Parker MacCready, Neil Banas (UW Oceanography)

The MoSSea model is a three dimensional simulation of Salish Sea and adjacent coastal waters implemented in ROMS (Regional Ocean Modeling System). A paper by Sutherland et al. (J Phys Oceanogr, 2011) documents an extensive validation against salinity, temperature, and velocity time series (Ecology monthly monitoring; ORCA high-resolution time series; moored coastal observations from NOAA and NSF projects) for a model hindcast of 2006. This model and its variants are currently being used for 1) evaluation of climate impacts on Puget Sound aquaculture using downscaled model projections of 2040s conditions; 2) mapping of connectivity between Puget Sound rivers and subbasins, including a spatially detailed attribution of fecal coliform, DIN, and freshwater loading to their watersheds of origin; 3) evaluation of climate impacts on *Alexandrium* harmful algal blooms (HABs) in Puget Sound; 4) hindcasting of *Pseudonitzschia* HABs, hypoxia, ocean-acidification patterns in Washington coastal waters, including the source waters for the Salish Sea; 5) exploration of energy dynamics and flow over rough topography; and 6) nesting within the global CESM climate model to explore effects of unresolved freshwater sources. (Funding for these projects comes from EPA, NOAA Ecohab, NSF, and DOE).

The extensively validated, custom biogeochemical model used for this coastal project (Banas et al, J Geophys Res, 2009; Davis et al. in prep, Siedlecki et al. in prep) is ready to be ported to Salish Sea waters and re-validated, pending new support. The coastal biogeochemical model includes a well-validated simulation of bottom oxygen and preliminary hindcasts of pH and other ocean-acidifcation variables (S Siedlecki, UW).

<u>Puget Sound Toxics Box Model</u>

Model development lead:
Greg Pelletier (Ecology)

This model is a coarse scale (20 model cells over the Puget Sound domain) used to analyze fate and transport of PCBs in the water column and sediments, coupled with a food web model to estimate bioaccumulation in marine biota. Building on the PCB work, a new model setup to analyze PAH, PBDEs, and selected metals is underway.

<u>South Sound Model</u>

Model development leads:
Greg Pelletier, Mindy Roberts, Anise Ahmed (Ecology)

This model is under development (see reference listing below) by Ecology with EPA funding. The model, built with the GEMSS model framework/software, simulates nutrients/dissolved oxygen for the South Sound. Ecology is currently in the process of calibrating the model for prediction of future impacts of human-caused nutrient pollution on dissolved oxygen conditions in the South Sound. The focus of the current study is large scale changes to oxygen in the main basins.

Puget Sound Central Basin food web model

Model development lead:
Chris Harvey (NOAA-NMFS, NWFSC)

This model was developed collaboratively by numerous scientists from NOAA, State of Washington agencies, and from the University of Washington. It was made in the Ecopath with Ecosim (EwE) software, which first creates a mass-balanced food web of functional groups linked through predator-prey interactions (Ecopath) and then allows the user to perturb the food web in a dynamic simulation framework (Ecosim). The model domain is the central basin of Puget Sound (marine waters from approximately Whidbey Island in the north to the Tacoma Narrows in the south); as EwE has essentially no spatial resolution, the model domain is treated as a single well-mixed box, although the developers have used some features of the model to impose some spatial dynamics (e.g., habitat effects related to eelgrass beds). The model food web is composed of over 65 functional groups, ranging from phytoplankton to marine mammals, and also includes 15 different fishing gear types.

The model is intended to be a support tool for management strategy evaluation, in relation to restoration goals outlined by the Puget Sound Partnership. Published applications to date include: reconstructions of recent time series data; evaluation of the ecosystem role of bald eagles; and estimating the ecosystem services provided by eelgrass. Work in progress includes an assessment of the performance of species and food web Vital Sign indicators as proxies for important community attributes, and estimating the potential direct and indirect impacts of ocean acidification on the community.

Salish Sea Atlantis Ecosystem Model

Model development lead:
Chris Harvey (NOAA-NMFS, NWFSC)

This model is in an early stage of development, led by scientists at NOAA with potential collaborators at State of Washington agencies, the University of Washington, and CSIRO-Australia. It is being developed in the Atlantis software, developed at CSIRO-Australia. When completed, the model will be a spatially and temporally explicit, biophysically coupled model that simulates ecosystem dynamics in most of the marine waters of the Salish Sea. The spatial domain will span from South Puget Sound to the southern Strait of Georgia (though likely not including the Strait of Juan de Fuca, the Fraser River delta, or north of the Fraser River). This area has been divided into >60 polygons based on circulation, bathymetry, benthic habitats, species composition, and resource management. Each polygon has multiple depth layers. Inputs from circulation models will drive the physics (water fluxes, temperature) and basic water chemistry (salinity, some nutrients, and point source inputs such as rivers or urban outfalls). Overlying the model's three-dimensional box geometry and oceanography will be a dynamic food web model with considerably greater detail than is used in EwE (see above). For example, vertebrate groups have substantially more explicit age structure, reproductive biology, depth and habitat preferences, movement behavior, and size-specific feeding ecology in Atlantis compared to EwE. The model has >50 different food web groups, again ranging from phytoplankton to marine mammals. The model will also simulate spatially and temporally dynamic fishing fleets. Atlantis can also model scientific monitoring, such that a simulated research program is collecting samples in space and time and those limited data (i.e., limited relative to the scope of the model) can be used to assess perceived responses in space and time to natural variability and prescribed management actions. This, then, would represent a spatiotemporally explicit "end-to-end" model for comparing potential outcomes of management activities and identifying potential tradeoffs at the scale of most of the Salish Sea.

USGS Sediment Transport Model of Salish Sea

Model development leads:
Guy Gelfenbaum and Andrew Stevens (USGS, Santa Cruz, CA)

The U.S. Geological Survey has developed a coupled hydrodynamic and sediment transport model for the Salish Sea using the Delft3D modeling system. A curvilinear grid consisting of approximately 129,000 grid cells covers the Strait of Juan de Fuca, Georgia Basin and Puget Sound. Delft3D solves the unsteady shallow water equations to simulate water motion due to tides, waves, wind, and buoyancy effects. Waves are simulated using the third-generation SWAN wave model. The wave- and flow- models are coupled: water levels, wind, and currents from the flow model are incorporated into the wave calculations and output from the wave model is used by the flow model to simulate enhanced bed stresses due to waves and wave-driven currents. Sediment transport of multiple sediment fractions, including both non-cohesive and cohesive sediment types, is included. Suspended sediment transport is solved using the advection-diffusion solver and bedload transport is calculated using standard nonlinear empirical relationships. The USGS Salish Sea model is primarily used to generate boundary conditions for detailed model applications at specific sites throughout the Salish Sea.

Coastal Hazards/Resilience Model

Puget Sound Coastal Resilience Tool
Nooksack, Skagit, Stillaguamish, Snohomish, Nisqually and Skokomish Deltas
Eric Grossman, Peter Horne, Chris Curran, Roger Fuller, Zach Ferdana, Greg Guannel, Alan Hamlet

A new web-based Puget Sound Coastal Resilience Tool helps managers and scientists assess the cumulative impacts of coastal hazards on ecosystems, infrastructure and communities. It also examines the role that coastal habitats serve to buffer future inundation impacts helping to prioritize restoration, hazard mitigation, and climate change adaptation efforts. We link downscaled global and regional Weather Research and Forecasting (WRF) climate predictions out to the year 2100 to the Variable Infiltration Capacity model to predict future runoff. Variability in winter peak and summer low stream flows is strongly associated with retreating glaciers, a transition to increasing precipitation as rainfall, and a rise in the snowline. Predicted runoff is then fed through recently improved fluvial sediment rating curves, which suggest significant increases in future sediment delivery that will likely influence stream channel aggradation and flood conveyance. Hydrodynamic models of the future projected stream flows are simulated with a range of sea-level rise and storm surge scenarios that induce backwatering affects and modify coastal groundwater levels. The Natural Capital Project's InVest Nearshore Protection Model simulates nearshore wave shoaling. The first version of the tool covers the large river deltas of the Nooksack, Skagit, Stillaguamish, Snohomish, Nisqually and Skokomish. It includes gradients in vertical land motion, sedimentation, and storm surge/waves and is augmented by hydrodynamic models (Delft3D, XBEACH, SWAN). The Coastal Resilience Tool provides spatial and temporal forecasts of the magnitude and probability of joint occurring coastal hazards that will affect ecosystems and land use planning. It provides a research and monitoring framework to test and refine our understanding of physical processes that affect coastal change and resilience.

Individual Embayment Models

In addition to the large scale models described above, there are several models of individual embayments within Puget Sound, including:

- Budd Inlet (nutrients/dissolved oxygen, Ecology)
- Oakland Bay (bacteria, Ecology)
- Quartermaster Harbor (nutrients/dissolved oxygen, King County)
- Hood Canal (nutrients/dissolved oxygen, UW: Kawase et al.)
- Dyes/Sinclair Inlet (bacteria and copper, U.S. Navy)
- Nisqually Delta, Elwha River, Deschutes Estuary, and Possession Point (sediment transport, USGS)

Gaps in Model Development, Monitoring Data, Application, and Maintenance

Development Gaps

1) Current biogeochemical models (PSGB and South Sound) can simulate main basins with reasonable accuracy but not shallow basins and portions of Hood Canal. Accurate analysis of these areas is within reach but will require additional model development, including development of refined model grids and inputs. Candidates for future development work include incorporation of sediment diagenesis subroutines into existing models, addition of submerged aquatic vegetation, and sediment toxics modules.

2) The MoSSea Salish Sea model is a circulation-only model at this time and is not funded to incorporate biogeochemistry. Porting the MoSSea coastal water quality model to the MoSSea Salish Sea simulation would give us two water quality models (PSGB and MoSSea) of the entire Salish Sea that can be systematically compared to identify relative strengths and areas of

potential improvement. In addition, this capability puts UW in a position to pursue water quality modeling-related grant funding from sources not available to Ecology.

3) Current models do not simulate pH and carbon chemistry. Analysis of acidification and the relationship between local nutrient/carbon inputs and global CO2 influence in Puget Sound will require additional model development.

4) Model updates and improvement over time. For example, continue priority improvements in the models, such as adding new parameters not currently simulated (e.g., suspended solids/turbidity, zooplankton), improved boundary conditions (e.g., Johnstone Strait representation at northern Salish Sea boundary), and model parameter re-calibration.

5) Maintain model diversity. The expertise of the Ecology/PNNL and UW Oceanography teams encompasses key areas of study, including nearshore dynamics, water quality/chemistry, plankton biology and coastal/estuarine physics). It is crucially important that there be several active modeling groups in the region. This fosters greater breadth of approaches to problem solving, the creation and sharing of forcing and validation data sets, the sharing of successful techniques, and the critical evaluation of results. Moreover, different users and funding agencies will be better served if our modeling community is both interactive and diverse.

6) The Atlantis model has the potential to be integrated with the biogeochemical models (e.g., PSGB and MoSSea). The circulation models must be spatially integrated to match the geometry of the Atlantis grid cells. Other basic needs for Atlantis include: a dedicated technician to lead literature and database searches and continue parameter development, additional computing resources, and code additions to address issues such as hypoxia, ocean acidification, or contaminant concentrations.

Estimated funding required to fill the gap:

Shallow basins and Hood Canal: $300,000 per basin
Re-calibrate MoSSea coastal biogeochemistry model for the Salish Sea: $200,000
Add pH simulation capability to PSGB, including calibration, sensitivity tests/scenarios, and documentation: $300,000
Add pH simulation capability to MoSSea including calibration, sensitivity tests/scenarios, and documentation: $300,000
Annual model improvements and documentation for MoSSea and PSGB: $100,000 per model per year
Model intercomparison and coordination for MoSSea and PSGB: $50,000
Atlantis development, including integration with MoSSea and PSGB: $125,000

Monitoring Data Needs

Existing long term monitoring programs for Puget Sound marine waters and major tributaries are providing a reasonable information base for model development, but there are important gaps that increase uncertainty and error in the biogeochemical models. These gaps will be shared/discussed with the PSEMP Marine Monitoring workgroup as they identify and prioritize gaps and priorities in marine monitoring:

1) Oceanic boundary monitoring. The temporal and spatial resolution of this monitoring is critical to accurately simulating conditions in the interior of Puget Sound. Areas of interest include Strait of Juan de Fuca and Johnstone Strait. Model quality is affected by limited frequency, spatial coverage, and parameter list monitored by current buoy systems.

2) New, limited-term biological process studies in Puget Sound would reduce uncertainty in biogeochemical predictions: phytoplankton response to temperature, light, nutrients; grazer community composition over the season cycle; carbon and nutrient fluxes from the surface layer to the benthos. Model development without such information requires either extrapolation from process studies on the outer coast and/or reliance on poorly constrained literature ranges.

3) Limited-term studies of sediment oxygen demand and chemical flux. Models are generally showing sensitivity to sediment conditions and processes. There is a need to expand the current base of information on sediment oxygen demand and fluxes of ammonia and nitrate.

4) ORCA buoy monitoring. These specialized buoys provide high temporal resolution information for areas of interest. In particular they are crucial for temporal resolution of plankton blooms, which develop in 1-2 days, and may easily be missed by monthly sampling. Past deployment has been project-based but there is pending discussion of potential long term siting and operation.

5) Food web monitoring. Each modeled functional group requires (at a minimum) estimates of biomass, production or mortality rate, consumption rate, diet, and fishing mortality rates. Key areas include: Biomass estimates of key zooplankton (copepods, euphausiids, microzooplankton, gelatinous zooplankton, pelagic larval invertebrates, etc.) at representative nearshore and offshore sites; fishery-independent, depth-stratified estimates of demersal fish abundance and size structure; fishery-independent estimates of resident forage fish biomass, (particularly Pacific herring, for which monitoring has been scaled back dramatically by the State); and local estimates of seasonal diets for most consumers. May also include stable isotopes of N, C, and S.

6) Toxics monitoring to increase confidence in box model predictions of environmental concentrations in water, sediment, and biota. Needs include trends in toxics loading from major rivers, toxics concentration in suspended sediment in Puget Sound, toxics loading from direct groundwater, confirmation of PCB and PBDE concentrations at the ocean boundary, trends in

atmospheric deposition, and fate/transport/bioaccumulation within freshwater tributaries to the Sound.

7) Other monitoring, including:

Nearshore/Estuarine conditions – possibly using low cost buoys
Weather – additional stations to assess spatial variability and accuracy of weather models

Estimated funding required to fill the gap:

Constraint of biochemistry using biological process studies: $350,000 (one-time cost)
Sediment fluxes: Depends on number of sites and sampling periods
Oceanic boundary monitoring: Depends on scale of monitoring
ORCA buoys: $100,000 per buoy per year
Food web monitoring: Depends on scale of monitoring

Application Gaps

The Puget Sound/Georgia Basin Model is a new scientific tool, and it was developed to analyze nutrient pollution effects. MoSSea has so far been applied to assessment of the sensitivity of temperature, circulation, fecal-coliform loading from major rivers, and *Alexandrium* HAB dynamics to climate trends. A food web model for the central basin of Puget Sound (EwE) is developed, and a more sophisticated model (Atlantis) is under development. Much remains to be done in all these application areas, and there are numerous new possible applications in Puget Sound/Georgia Basin as well:

1. Sea Level Rise – Inundation and Salinity Intrusion. Predicting future nearshore inundation (coastal flooding) and water quality effects on estuaries.

2. Climate impacts on salmon migration and life cycles. Predicting potential warm temperature fronts near the mouths of estuaries (e.g., Snohomish and Stillaguamish), changes in circulation and olfactory corridors important to salmon migration; changes in the magnitude and timing of system-wide prey availability at critical times in salmon life history.

3. Hypoxia in shallow subbasins. Predicting potential increase in nutrient loads in shallow subbasins especially during conditions suitable for spring and summer blooms that could lead to hypoxia in the poorly flushed basins.

4. HAB impacts on aquaculture and human health. Predicting shifts in windows of opportunity, seasonal biological dynamics, and dispersion patterns of *Alexandrium*, *Heterosigma*, and other HAB species.

5. Ocean acidification impacts (pH) - Predicting the movement of this upwelled acidic nutrient rich water into Puget Sound and understanding its interaction with loads from point and nonpoint sources of nutrients and carbon.

6. Operational modeling – Daily forecasting. This will improve model evaluation and skill over time, and it will also create an opportunity for a web-based system to provide real-time Puget Sound currents, salinity, and water quality conditions. Potential uses for emergency response and oil spill contingency planning, prediction of HABs, and general public information for fishing and boating.

7. Food web modeling to estimate pathways and concentrations of contaminants in the food web, examining the sensitivity of key food web groups to historically documented system changes (e.g., decline of bottom fish), and comparing/contrasting management scenarios explicitly drawn from Puget Sound Partnership species and food web objectives and targets.

There is currently no funding to develop and apply the model(s) in these areas of interest. In addition, we lack funding for outreach to share the capabilities of the model(s) with other organizations and determine if existing model predictions can assist them in their Puget Sound work.

Estimated funding required to fill the gap:

Outreach and providing existing model prediction data: $100,000 per year

Potential future model applications: $50,000 to $500,000 per project depending on scope

Maintenance Gaps

Both the Puget Sound/Georgia Basin Model and MoSSea were developed using project-based funding, but models are tools that require ongoing maintenance to insure their utility over time. For example, EPA's Chesapeake Bay program sets aside a substantial annual budget for its modeling program. Puget Sound does not currently have such a modeling support system in place. For example, the following support has not been secured for either PSGB or MoSSea.

1. Maintenance/improvement of computer systems to run the model efficiently and store data
2. Model code updates and corrections
3. Additional simulation years

Estimated funding required to fill the gap for maintenance of PSGB and MoSSea: ($80K per model per year)

Summary Table of Cost Estimates

Category	Model	Task	Cost	One-time or ongoing	Priority	Rationale for Priority
Maintenance	PSGB and MoSSea	Maintenance of computer systems; Model code updates and corrections	$160,000 per year ($80,000 per model)	Ongoing	Very High	Project funds have enabled construction of these models but there is no long term maintenance funding. Models will only be available for future project-funded work if maintained over long term.
Development	PSGB and MoSSea	Ongoing priority improvements in the models	$200,000 per year ($100,000 per model)	Ongoing	Very High	Model improvement when warranted by new information or error identification is a fundamental activity for a model in active use.
Application	PSGB And MoSSea	Outreach and providing existing model prediction data	$100,000 per year ($50,000 per model)	Ongoing	Very High	This funding would support outreach to other state, fed, local govts and tribes and simple tasks such as providing existing predictions of interest or scoping future work that incorporates new modeling information.
Development	MoSSea	Add water quality prediction capability, including calibration and documentation	$200,000	One-time	High	This will provide a second water quality model alongside PSGB. Multiple models provide add'l info to bound uncertainty (similar to climate change ensemble of models). Enables university to provide water quality model services in addition to Ecology/PNNL.
Development	MoSSea	Add pH simulation capability, including calibration, sensitivity tests, scenarios and documentation	$300,000	One-time	High	Ocean acidification interest/concern is high. This includes all tasks to provide estimation of a range of conditions expected in the future, local/global contributions, etc. This includes calibration/testing, assessment of mechanisms controlling short- and long-term variability, and ensemble projection of future conditions.
Development	PSGB	Add pH simulation capability, including calibration, sensitivity tests, scenarios and documentation	$300,000	One-time	High	Ocean acidification interest/concern is high. This includes all tasks to provide estimation of a range of conditions expected in the future, local/global contributions, etc. This includes calibration/testing, assessment of mechanisms

						controlling short- and long-term variability, and ensemble projection of future conditions.
Development	All	Constraint of biochemistry model constants using biological process studies	$350,000	One-time	Medium	Models can be developed without this site-specific data, but uncertainty would likely be reduced with these studies.
Development	All	Model intercomparison and coordination	$50,000	One-time	Medium	If MoSSea is funded to full water quality capability (above), then this task would provide valuable information to reduce uncertainty and align co-development of both models.
Development	Atlantis	Develop model to incorporate data from PSGB and/or MoSSea; incorporate code changes for hypoxia, acidification, etc.	$125,000	One-time	Medium	Estimated funding required to fill gaps: $35K for physical oceanography modeling, $60K for technician, $10K for computers, $20K for other Atlantis code updates.
Application	All	Potential future model applications, such as: predictions of sea level rise, ocean acidification, shallow bay hypoxia, Lower Hood Canal hypoxia, and real-time conditions (operational model)	$50,000 to $500,000 per project	Future one-time	NA	This is a placeholder showing that model application projects will depend on Lead Organization and Partnership planning and priorities.
Monitoring	All	See listing of needs above		Mix	NA	This is a placeholder. The Modeling and Marine Monitoring workgroups will coordinate and the Marine Monitoring gap document will reflect priority.
TOTAL GAPS Annual maintenance, development, and outreach/data products for PSGB and MoSSea: $460,000 per year ($230,000 for each model) One-time task needs: $1,325,000 Future individual projects: $50,000 to $500,000 per project						

References

[a] PSGB Model

Website:
www.ecy.wa.gov/programs/wq/PugetSound/DOModel.html

[a1] Biogeochemical model references:

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Winter DF, Banse K, Anderson GC (1975). The dynamics of phytoplankton blooms in Puget Sound, a fjord in the northwestern United States. Mar Biol 29:139–176

[a2] Circulation model reference:

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[b] MoSSea Model

Website:
http://faculty.washington.edu/pmacc/cmg/cmg.html (the UW Coastal Modeling Group)
http://faculty.washington.edu/pmacc/MoSSea/ (specific to the MoSSea project)

[b1] Biogeochemical model references:

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[b2] Circulation model reference:

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[c] Puget Sound Toxics Box Model

[c1] Circulation model

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[d] South Sound Model

Website:
http://www.ecy.wa.gov/puget_sound/dissolved_oxygen_study.html

Biogeochemical model poster:
https://fortress.wa.gov/ecy/publications/publications/1103059.pdf

[e] Hood Canal Dissolved Oxygen Model

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An integrated watershed and receiving water model was developed to simulate fecal coliform (FC) fate and transport in Sinclair and Dyes Inlets, Puget Sound, WA [h1]. Consisting of a watershed model, an empirical FC loading model, and an estuarine fate and transport model, the integrated model was used to support development of a TMDL implementation plan for the Inlet [h2]. The modeling system was also used to simulate out migration of juvenile salmon from the watershed [h3] and copper loading and speciation within the Inlets [h4]. Present work is developing the capability to model near field mixing of complex discharges under dynamic conditions [h4].

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